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# Differential Evolution Based Optimization Approach for Power Factor Correction

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***Abstract-*** **In radial distribution systems, the voltages at buses reduces when moved away from the substation, also the losses are high. The reason for decrease in voltage and high losses is the insufficient amount of reactive power, which can be provided by the shunt capacitors. For this purpose, in this paper, two stage methodologies are used. In first stage, the load flow of pre-compensated distribution system is carried out using 'Dimension reducing distribution load flow algorithm'. In the second stage, Differential Evolution (DE) technique is used to determine the optimal location and size of the capacitors. The above method is tested on IEEE 69 bus system. In this paper a new method is proposed to improve the power factor of those buses having low power factor (less than 0.8lag) to unity power factor simultaneously by placing the capacitors.**

***Index Terms-*** **Electrical Distribution System, Optimal Capacitor Placement, Dimension reducing distribution load flow algorithm (DRDLFA), Differential Evolution (DE) Algorithm, power factor correction.**

## I. Introduction

Capacitors are generally used for reactive power compensation in distribution systems. The purpose of capacitors is to minimize the power and energy losses and to maintain better voltage regulation for load buses and to improve system security. The amount of compensation provided with the capacitors that are placed in the distribution network depends upon the location, size and type of the capacitors placed in the system [1]. A lot of research has been made on the location of capacitors in the recent past [2] without including the installation cost of the capacitors. All the approaches differ from each other by the way of their problem formulation and the problem solution method employed. Some of the early works could not take into account of capacitor cost. In some approaches the objective function considered was for control of voltage. In some of the techniques, only fixed capacitors are adopted and load changes which are very vital in capacitor location was not considered. Other techniques have considered load changes only in three different levels. A few proposals were schemes for determining the optimal design and control of switched capacitors with non-simultaneous switching [3]. It is also also very important to consider the problem solution methods employed to solve the capacitor placement problem, such as gradient search optimization, local variation method, optimization of equal area criteria method for fixed capacitors and dynamic programs [4]. Although these techniques have solved the problem, most of the early works used analytical methods with some kind of heuristics. In doing so, the problem formulation was oversimplified with certain assumptions, which was lacking generality. There is also a problem of local minimal in some of these methods. Furthermore, since the capacitor banks are non continuous variables, taking them as continuous compensation, by some authors, can cause very high inaccuracy with the obtained results. A differential evolution algorithm (DEA) is an evolutionary computation method that was originally introduced by Storn and Price in 1995 [5]. Furthermore, they developed DEA to be a reliable and versatile function optimizer that is also readily applicable to a wide range of optimization problems [6]. DEA uses rather greedy selection and less stochastic approach to solve optimization problems than other classical EAs. There are also a number of significant advantages when using DEA, which were summarized by Price in [7]. Most of the initial researches were conducted by the differential evolution algorithm inventors (Storn and Price) with several papers [8] which explained the basis of differential evolution algorithm and how the optimization process is carried out. In this respect, it is very suitable to solve the capacitor placement or location problem. IEEE 69 bus distribution system is considered for case study. The test system is a 12.66 KV, 10 KVA, 69-bus radial distribution feeder consisting of one main branch and seven laterals containing different number of load buses. Buses 1 to 27 lie on the main branch. Bus #1 represents the substation feeding the distribution system.

## II. Distribution Load Flow

The distribution systems are characterized by their prevailing radial nature and high R/X ratio. This renders the load flow problem ill conditioned. So many methods [9-14] have been developed and tested ranging from sweep methods, to conic programming formulation. The relationship between the complex branch powers and complex bus powers is derived as a non singular square matrix known as element the equations are expressed in matrix format. This proposed dimension Reducing load flow method could be applied to distribution systems having voltage-controlled buses also.
Notations

N-no of buses
I ij -Branch current flowing through element ij
I j -Bus current of node j




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V j -Bus voltage of node j
S ij -Complex power flowing from node i to node j
S ji-Complex power flowing received at node j from node i
S j-Specified Bus power at bus j
Z ij-Impedance of element ij
TL ij-Transmission loss of element ij

The power flow method is summarized as follows:

1. For the first iteration transmission losses are initialized as zero for each element.

2. From the bus powers specified the branch powers are determined as per equation (1&2).

$$I_{branch} = K^{-1} I_{bus} \tag{1}$$

$$S_{bus} = K\left[S_{branch}^{sending} - TL_{branch}\right] \tag{2}$$

3. The variable Rij. is determined for each element using equation 3

$$S_{ij} = P_{ij} + iQ_{ij} = R_{ij} Y_{ij}^{*} \tag{3}$$

4. The bus voltage, branch current and bus current are determined from Rij.

$$V_j = V_i - \frac{R_{ij}^{*}}{V_i^{*}} \tag{4}$$

$$I_{ij} = \frac{R_{ij}^{*}}{V_i^{*}} Y_{ij} \tag{5}$$

5. The bus currents are determined

$$P_i + Q_i = \sum_{i \in k(i)} P_{ij} + iQ_{ij} = \sum_{i \in k(i)} V_i (V_i^{*} - V_j^{*}) Y_{ij}^{*} \tag{6}$$

And from (6) bus powers are calculated. Since the transmission losses are neglected in the first iteration there will be mismatch between the specified powers and calculated powers. The mismatch is a part of the transmission loss. TLijr is the transmission loss part for 'ij'th element for 'r'th iteration. Transmission loss of each element is the summation of the transmission loss portions of all previous iterations.

$$TL_{ij} = \sum {}^{r}TL_{ij} \tag{7}$$

'r' Where is the Iteration count

$$TL_{ij}^{r} = S_j^{spec} - {}^{r-1}V_j \cdot {}^{r-1}I_j^{*} \tag{8}$$

$$S_{ji} = S_{ij} - TL_{ij}$$

$$S_{branch}^{receiving} = S_{branch}^{sending} - TL_{loss} \tag{9}$$

$$\max(TL_{ij}^{r}) \leq \varepsilon$$

Treatment of voltage controlled buses If power is fed from multiple ends of the radial system, other feeding buses except slack bus are treated as voltage controlled buses. The equation is as follows.

$$R_{ij} = V_i (V_i^{*} - V_j^{*}) \tag{10}$$

The trigonometric equations are to be solved to get the phase angle of each PV bus j and the reactive power can be updated as

Equation 10 is modified for the jth voltage controlled bus.

$$real(S_{ij}) = P_{ij} = real(R_{ij} Y_{ij}^{*}) \tag{12}$$

$$R_{ij} = X_{ij} + iY_{ij} \tag{11}$$

$$P_{ij} = real((X_{ij} + iY_{ij})(G_{ij} + iB_{ij})) \tag{13}$$

$$P_{ij} = G_{ij}(|V_i|^2 - |V_i||V_j|\cos(\phi_{12})) - B_{ij}|V_i||V_j|\sin(\phi_{12})$$

$$\frac{G_{ij}|V_i|^2 - P_{ij}}{|V_i||V_j|} = G_{ij}\cos(\phi_{12}) - B_{ij}\sin(\phi_{12}) \tag{15}$$

$$Q_{ij} = B_{ij}(|V_i|^2 - |V_i||V_j|\cos(\phi_{12})) - G_{ij}|V_i||V_j|\sin(\phi_{12}) \tag{16}$$

Then the same procedure described for the PQ buses is carried out till the convergence.

## III. Powerfactor Correction

By supplying leading KVAR with the addition of the capacitor, the total lagging KVAR required by the load can effectively be reduced and the apparent power S of the load can be reduced. This effectively decreases the power factor angle and improves the power factor. The generation of reactive power at a power plant and its supply to a load located at a far distance is not economically feasible, but it can easily be improved by capacitors located at the load centers.

Assume that a load is supplied with a real power P, lagging reactive power $Q_1$, and apparent power $S_1$ at a lagging power factor of

$$\cos\theta_1 = P_1/S_1; \text{ where } S_1 = (P_2 + Q_2)^{1/2} \tag{17}$$

When a shunt capacitor of $Q_c$ is installed at the load, the power factor can be improved from $\cos\theta_1$ to $\cos\theta_2$,

$$\text{where } S_2 = [P_2 + (Q_1 - Q_c)^2]^{1/2};\ Q_1 = Q_2 + Q_c \tag{18}$$

Thus the power factor correction produces economic savings in capital expenditures and fuel expenses through a release of kilovolt ampereage capacity.

a. Savings Calculations Due To Power Factor Correction

- PSE Rate Schedule:
- Energy Rate = $4.08 per KWH
- Energy Rate = $4.08 per KWH

## IV. Differential Evolution

Differential Evolution is relatively a newer addition to the population based search algorithms. DE was first suggested by Storn and Price in 1995 as a search technique for solving optimization problems. It uses the same operators like mutation, crossover and selection as that of GA but manipulates them in a manner different to that of GA. Differential Evolution (DE) has proven to be a promising candidate for minimizing real valued, multi-nodal objective functions. Besides it has good convergence properties. DE is very simple to understand and to implement.



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Differential evolution (DE) is a population-based stochastic optimization algorithm for real-valued optimization problems. In DE each design variable is represented in the chromosome by a real number. The DE algorithm is simple and requires only three control parameters: weight factor (F), crossover rates (CR), and population size (NP). Three main steps of DE, mutation, crossover, and selection were performed sequentially and were repeated during the optimization cycle. Figure 1 gives the flowchart of DE.

*a. De Implementation*

The basic procedure of DE is summarized as follows.

Step 1: Randomly initialize population of individual for DE.

Step 2: Evaluate the objective values of all individuals, and determine the best individual.

Step 3: Perform mutation operation for each individual in order to obtain each individual's corresponding mutant vector.

Step 4: Perform crossover operation between each individual and its corresponding mutant vector in order to obtain each individual's trial vector.

Step 5: Evaluate the objective values of the trial vectors.

Step 6: Perform selection operation between each individual and its corresponding trial Vector so as to generate the new individual for the next generation.

Step 7: Determine the best individual of the current new population with the best Objective value then updates best individual and its objective value.

Step 8: If a stopping criterion is met, then output gives its bests and its objective value.

Otherwise go back to step 3.

## V. Mathematical Formulation

The cost function is formulated and it can be represented by the equation 3.1 [15].

$$C = K_E TP + \sum_{i=1}^{ncap} (K_c Q_{ci} + K_{cf}) \quad (19)$$

C Total cost in $

$K_E$ Factor to convert energy losses to dollars = $0.06/KWH

T Load Duration in Hours

P Real Power loss in KW

$K_c$ Capacitor Cost = $ 3/KVAR

$Q_{ci}$ Reactive power injection from capacitor to node i

$K_{cf}$ Capacitor Installation Cost = 1000$/KVAR

ncap Number of Capacitor locations

## VI. Case Study And Results

Prior to capacitor installation, a load flow program based on Dimension Reducing Distribution load flow method is run to obtain the present system conditions. The proposed solution methodologies have been implemented in MATLAB 7.10.0. The solution algorithm is based on DE algorithm and tested on IEEE 69 Bus System in Fig.2 which has been designed to find the optimal solution for this problem.

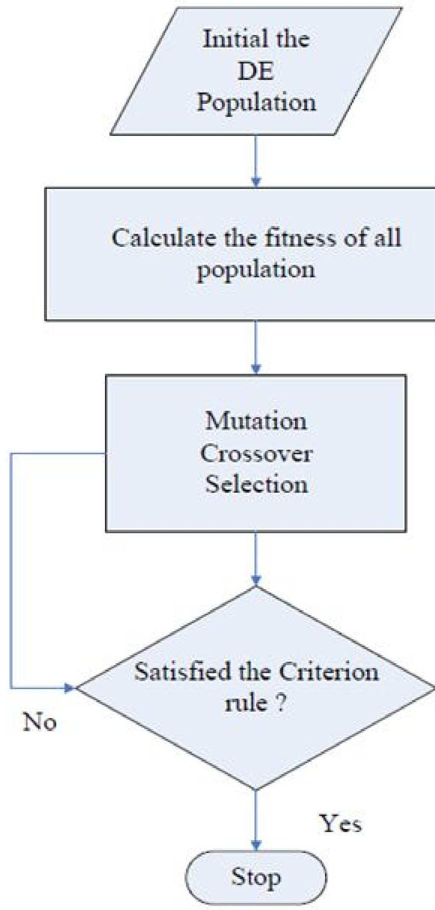


Fig 1: Differential Evolution flowchart

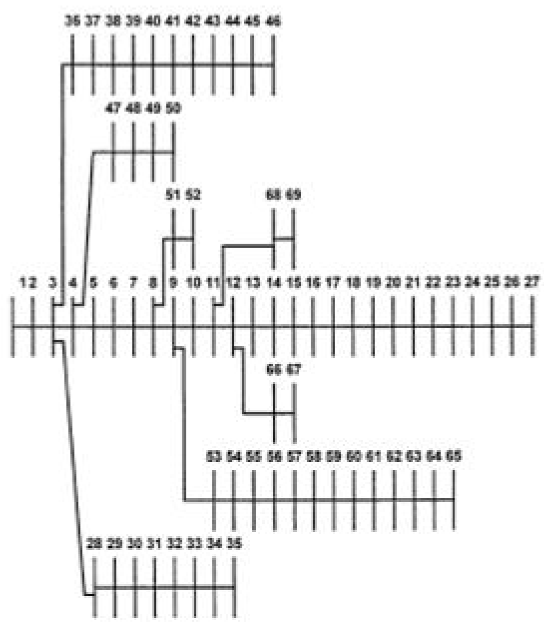

Fig 2: IEEE 69 Bus System

The parameters are defined as shown below:

Elapsed time: 92.38 Sec; Gmax = 800; F: 0.8; CR: 0.8; NP: 100



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TABLE 1: POWER FACTOR CORRECTION

| Bus No. # | Old p.f | New p.f | Capacitor rating required in KVAR |
|---|---|---|---|
| 5 | 0.7633 | 1 | 2.2 |
| 9 | 0.7791 | 1 | 3.5 |
| 40 | 0.768 | 1 | 1.0 |

Table 1 shows that there are three buses having low power factor i.e less than 0.8 out of 69 buses and the buses are #5, #9 and #40. The rating of the additional capacitors required for power factor correction to unity power factor simultaneously at buses #5, 9 and 40 are 2.2, 3.5 and 1.0 KVAR respectively.

TABLE II: SAVINGS DUE TO POWER FACTOR CORRECTION

| | Bus No. #5 | Bus No. #9 | Bus No. #40 |
|---|---|---|---|
| Savings in Energy usage in $/year | 1938.84 | 3054.72 | 879.12 |
| Savings due to pf. improvement in $/year | 2890.8 | 4599 | 1314 |
| Total savings in $/year | 4829.64 | 7653.72 | 2193.12 |

Table 2 gives savings that can be obtained by correcting the power factor to unity at the buses #5, #9 and #40 by placing the additional capacitors. Table 3 gives the ratings of the capacitors required only for improving the voltage profile and reducing the losses using DE.

TABLE III: KVAR REQUIRED ONLY FOR IMPROVING THE VOLTAGE PROFILE AND REDUCING LOSSES USING DE

| Optimal Location | Optimal Size of the capacitor |
|---|---|
| Bus No #16 | 200 KVAR |
| Bus No #60 | 700 KVAR |
| Bus No #61 | 500 KVAR |

Table 4 gives the total KVAR capacity required including additional capacitors to improve the power factors of the weak buses to unity in addition, to improve the voltage profile and to reduce the energy losses using DE on IEEE 69 Bus System.

TABLE IV: TOTAL KVAR PLACED INCLUDING ADDITIONAL CAPACITORS ON IEEE 69 BUS SYSTEM FOR P.F.C USING DE

| Optimal Location | Optimal Size of the capacitor |
|---|---|
| Bus No #16 | 200KVAR |
| Bus No #60 | 700 KVAR |
| Bus No #61 | 500 KVAR |
| Bus No # 5 | 2.2 KVAR |
| Bus No # 9 | 3.5 KVAR |
| Bus No # 40 | 1.0 KVAR |

TABLE 5: COMPARISON OF PER UNIT VOLTAGES OF IEEE 69 BUS SYSTEM OF DE METHOD BEFORE AND AFTER P.F. CORRECTION

| Bus No. # | Voltage in (p.u.) before placing capacitors | Voltage in (p.u.) using DE after placing capacitor | Voltage in (p.u.) using DE after p.f. correction |
|---|---|---|---|
| 1 | 1.0000 | 1.0000 | 1.0000 |
| 2 | 1.0000 | 1.0000 | 1.0000 |
| 3 | 0.9999 | 1.0000 | 1.0000 |
| 4 | 0.9998 | 0.9999 | 0.9999 |
| 5 | 0.9990 | 0.9994 | 0.9994 |
| 6 | 0.9901 | 0.9923 | 0.9923 |
| 7 | 0.9808 | 0.9849 | 0.9849 |
| 8 | 0.9786 | 0.9831 | 0.9832 |
| 9 | 0.9774 | 0.9823 | 0.9823 |
| 10 | 0.9724 | 0.9776 | 0.9777 |
| 11 | 0.9713 | 0.9766 | 0.9766 |
| 12 | 0.9682 | 0.9738 | 0.9738 |
| 13 | 0.9653 | 0.9713 | 0.9713 |
| 14 | 0.9624 | 0.9689 | 0.9689 |
| 15 | 0.9595 | 0.9665 | 0.9665 |
| 16 | 0.9589 | 0.9661 | 0.9661 |
| 17 | 0.9581 | 0.9653 | 0.9654 |
| 18 | 0.9581 | 0.9653 | 0.9654 |
| 19 | 0.9576 | 0.9649 | 0.9649 |
| 20 | 0.9573 | 0.9646 | 0.9646 |
| 21 | 0.9568 | 0.9641 | 0.9641 |
| 22 | 0.9568 | 0.9641 | 0.9641 |
| 23 | 0.9567 | 0.9640 | 0.9640 |
| 24 | 0.9566 | 0.9639 | 0.9639 |
| 25 | 0.9564 | 0.9637 | 0.9637 |
| 26 | 0.9563 | 0.9636 | 0.9636 |
| 27 | 0.9563 | 0.9636 | 0.9636 |
| 28 | 0.9999 | 0.9999 | 0.9999 |
| 29 | 0.9999 | 0.9999 | 0.9999 |
| 30 | 0.9997 | 0.9998 | 0.9998 |
| 31 | 0.9997 | 0.9997 | 0.9997 |
| 32 | 0.9996 | 0.9996 | 0.9996 |
| 33 | 0.9993 | 0.9994 | 0.9994 |
| 34 | 0.9990 | 0.9990 | 0.9990 |
| 35 | 0.9989 | 0.9990 | 0.9990 |
| 36 | 0.9999 | 0.9999 | 0.9999 |
| 37 | 0.9997 | 0.9998 | 0.9998 |
| 38 | 0.9996 | 0.9996 | 0.9996 |
| 39 | 0.9995 | 0.9996 | 0.9996 |
| 40 | 0.9995 | 0.9996 | 0.9996 |
| 41 | 0.9988 | 0.9989 | 0.9989 |
| 42 | 0.9986 | 0.9986 | 0.9986 |
| 43 | 0.9985 | 0.9985 | 0.9985 |
| 44 | 0.9985 | 0.9985 | 0.9985 |
| 45 | 0.9984 | 0.9984 | 0.9984 |
| 46 | 0.9984 | 0.9984 | 0.9984 |
| 47 | 0.9998 | 0.9998 | 0.9998 |



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TABLE 5: COMPARISON OF PER UNIT VOLTAGES OF IEEE 69 BUS SYSTEM OF DE METHOD BEFORE AND AFTER P.F. CORRECTION

| | | | |
|---|---|---|---|
| 48 | 0.9985 | 0.9986 | 0.9986 |
| 49 | 0.9947 | 0.9948 | 0.9948 |
| 50 | 0.9942 | 0.9942 | 0.9942 |
| 51 | 0.9785 | 0.9831 | 0.9831 |
| 52 | 0.9785 | 0.9831 | 0.9831 |
| 53 | 0.9747 | 0.9802 | 0.9802 |
| 54 | 0.9714 | 0.9779 | 0.9779 |
| 55 | 0.9669 | 0.9746 | 0.9746 |
| 56 | 0.9626 | 0.9715 | 0.9715 |
| 57 | 0.9401 | 0.9538 | 0.9538 |
| 58 | 0.9290 | 0.9451 | 0.9451 |
| 59 | 0.9248 | 0.9417 | 0.9417 |
| 60 | 0.9197 | 0.9377 | 0.9377 |
| 61 | 0.9123 | 0.9325 | 0.9326 |
| 62 | 0.9120 | 0.9324 | 0.9324 |
| 63 | 0.9117 | 0.9321 | 0.9321 |
| 64 | 0.9098 | 0.9302 | 0.9302 |
| 65 | 0.9092 | 0.9296 | 0.9296 |
| 66 | 0.9713 | 0.9766 | 0.9766 |
| 67 | 0.9713 | 0.9766 | 0.9766 |
| 68 | 0.9678 | 0.9735 | 0.9735 |
| 69 | 0.9678 | 0.9735 | 0.9735 |

TABLE VI: SAVINGS DUE TO POWER FACTOR CORRECTION OF IEEE 69 BUS SYSTEM USING DE

| | Before placing capacitor | After placing the capacitor & before p.f. correction | After placing the capacitor & after p.f. correction |
|---|---|---|---|
| Energy loss cost / Year | 1,18,260$ | 77,767.77$ | 77,741.49$ |
| Saving due to reduction in Energy loss / year | - | 40,492.23$ | 40,518.51$ |
| Savings due to p.f. correction / year | - | - | 14,676.48$ |
| Total cost of the Capacitors (KVAR cost) | - | 4200$ | 4220.1$ |
| Installation cost of the Capacitors | - | 3000$ | 6000$ |
| Net Savings / Year | - | 33,292.23$ | 44,974.89$ |

Table 5 gives the comparison of Per Unit voltages of IEEE 69 Bus System before and after p.f. correction and Table 6 gives the savings due to power factor correction of IEEE 69 Bus System using DE. Finally the net savings before p.f. correction are 33,292.23$ and 44,974.89$ per annum after p.f. correction.

Table 7 gives comparison between savings due to power factor correction of IEEE 69 Bus System using DE and GA [15]. The reduction in real power losses is almost same in **I.** in both GA and DE. The total number of capacitors required using GA is 7 whereas for DE it is 6. Because of this the reduction in the installation cost of the capacitors is $1000 and also the total KVAR required in DE is 1406.7KVAR whereas in the case of GA it is 1506.7KVAR. Because of this also the reduction in the cost of the capacitors is $300. Therefore when compared to GA, DE is giving better savings. DE is the best method when compared to GA because of its savings, less number of capacitors to be installed and reduction in the installation cost of the capacitors even though there is slight improvement in the magnitudes of the voltage profile in GA when compared to DE.

TABLE VII: COMPARISON BETWEEN SAVINGS DUE TO POWER FACTOR CORRECTION OF IEEE 69 BUS SYSTEM USING DE AND GA

| | After placing capacitor & before p.f.c using GA[15] | After placing capacitor & after p.f.c. using GA[15] | After placing capacitor & before p.f.c. using DE | After placing capacitor & after p.f.c. Using DE |
|---|---|---|---|---|
| Energy loss cost / Year($) | 77,152.82 | 77,131.8$ | 77,767.77 | 77,741.49 |
| Savings due Energy loss reduction / year($) | 41,107.18 | 41,128.2$ | 40,492.23 | 40,518.51 |
| Savings due to p.f.c / year($) | - | 14,676.48$ | - | 14,676.48 |
| Total Capacitors cost ($) | 4,500 | 4,520.1 | 4,200 | 4,220.1 |
| Installation cost ($) | 4,000 | 7,000 | 3,000 | 6,000 |
| Net Savings / Year($) | 32,607.18 | 44,284.58$ | 33,292.23 | 44,974.89 |

## VII. CONCLUSION

Buses having low power factor (less than 0.8 lag) are identified for the IEEE 69 Bus System and their power factor had been improved to unity simultaneously with the help of additional capacitors by DE Algorithm along with the Dimension Reducing Load Flow method. The act of improving the power factor of the poor power factor buses to unity power factor has resulted in better voltage profile, reducing losses in spite of additional capacitors placed, due to further increase in savings because of power factor correction. In overall consideration the Differential Evolution algorithm method along with improvement of the poor power factor buses to unity power factor was found to give good voltage profile, reduced losses and improved savings from the point of view of annual savings with good performance this seems to be the Best Method.

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